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Changes in heat waves in Chile

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ABSTRACT

This research aims to examine changes in heat waves (HWs) over Chile from 1961 to 2016 using daily maximum (TX) and minimum temperature (TN) data recorded at 13 weather stations. Based on three HW-definitions and five aspects for each definition some 15 indices were calculated and analyzed for the extended summer period (November-March). The three definitions of the HWs employed in this study were based on: (1) the TX exceeding the 90th percentile for at least three consecutive days, (2) the TN exceeding the 90th percentile for at least three consecutive days, and (3) the positive values of excess heat factor (EHF) maintaining for at least three consecutive days. The five aspects calculated for each of the definitions provided information related to the frequency, duration, and intensity of HWs. Trends (be them increasing or decreasing), magnitude (change per decade) and statistical significance ($p < 0.05$) were identified using the ordinary least square method and the t-test. Therefore, in terms of HW aspects, the results of the HWs climate regime analysis showed that the most extreme region of Chile is the Atacama Desert, followed by the Santiago metropolitan area. Change analysis revealed that Chile experienced increasing trends in most of the HW data sets. Thus, the frequency of trend types of all HW indices time series showed an increasing trend of 79%. About 24% of the time series showed statistically significant increasing trends. Decreasing trends were found in about 20% of the analyzed data, less than 1% of which being statistically significant. Stationary trends were detected in only 2% of the series. The highest frequency of statistically significant increasing trends was found in the HWs identified based on TX, followed by those computed based on EHF. Regarding their aspects, the number of events had the highest frequency of significant increasing trends. In terms of spatial distribution, the most important changes were found in central Chile.

1. Introduction

Out of the natural hazards, heat waves (HWs) are known to have some of the most devastating consequences on human society and natural environment worldwide. Their occurrence is associated with a wide range of adverse impacts on a variety of systems including increased human morbidity and mortality (Unal et al., 2013; Loughran et al., 2017). The adverse impact of each aspect of HWs can affect humans differently. For example, the HW duration was found to have a high impact on human mortality (D'Ippoliti et al., 2010; Linares et al., 2015; Kim et al., 2016). A milder but prolonged HW can increase human discomfort, morbidity and mortality (D'Ippoliti et al., 2010; Zittis et al., 2016). The intensity of HWs was found to have an important impact on human health, as well (Anderson and Bell, 2011). Although HWs cause more death than any other natural hazard worldwide, they are often not perceived as a major danger mostly because HWs progress slowly compared to other natural disasters (e.g. tropical cyclones, floods, forest fires) and their damages are not easy to investigate (Kim et al., 2016). This can lead to an underestimation of HWs impact risks. HW aspects were also found to have a major negative effect on agriculture and water resources. Thus, duration of HWs has a high impact on agriculture production and water quality (Liu et al., 2015; Loughran et al., 2017). Moreover, long-duration HWs are usually associated with dry spells and can increase water demand and forest fire risk (Zittis et al., 2016). A short but intense HW can dramatically reduce the quantity and quality of crop yields (Zittis et al., 2016). Nighttime events also have negative consequences on various crops. For instance, high temperature during the night has a significant impact on grain yields (Hatfield and Prueger, 2015). Furthermore, HWs can damage infrastructure and put pressure on energy and water demands (Unal et al., 2013). Other factors such as the extensive urbanization along with the urban heat island effect could intensify the negative impact of HWs in urban areas (Zittis et al., 2016).

An HW is defined as a period of consecutive days with unusual high

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temperatures (Croitoru et al., 2016). Heat waves can be identified with a wide range of definitions based on different intensity and duration thresholds. Some definitions use only the maximum (TX) or minimum temperature (TN) exceeding either a fixed threshold (i.e. 25 °C, 30 °C, 32 °C, 33 °C, 35 °C, 37 °C) or a relative percentile-based intensity threshold (i.e. 85th, 90th, 95th, 98th, 99th percentile), while others refer to a combination of extreme temperatures exceeding a specific threshold. In terms of duration, an HW is in progress when the TX or/and TN exceed the established intensity threshold for at least two to six or even more consecutive days. Some definitions allow for a period of a day or two with non-HW conditions, while others break it in two or more events (Piticar et al., 2017). Other definitions are very specific when trying to identify an HW event. For example, the Netherlands Meteorological Institute uses the following definition: at least 5 days with TX above 25 °C, at least 3 days of which having a TX of > 30 °C. Yet, some current studies have showed that extreme heat events must attain certain thresholds of intensity and duration so as to significantly impact various systems (Montero et al., 2012; Nairn and Fawcett, 2015; Hatvani-Kovacs et al., 2016; Guo et al., 2017).

Many studies revealed that HWs have become more frequent, longer and more intense in different parts of the world in the last decades (Donat et al., 2013; Perkins and Alexander, 2013; Peterson et al., 2013; Keellings and Waylen, 2014; Shevchenko et al., 2014; Keggenhoff et al., 2015; Rusticucci et al., 2016; Croitoru et al., 2016; Rohini et al., 2016; Piticar et al., 2017). Recently, Mora et al. (2017) highlighted on the increased threat on human life caused by the climate conditions that exceed human thermoregulatory capacity, while additional factors, such as ageing population and increasing urbanization, could extend the consequences of exposure up to potentially deadly extreme climatic conditions (Mora et al., 2017). The analysis for future periods indicated that the changes in the HW aspects (frequency, duration, intensity) will persist at even higher rates (Ballester et al., 2010; Nakano et al., 2013; Amengual et al., 2014; Marengo et al., 2014; Russo et al., 2014; Murari et al., 2015; Schoetter et al., 2015; Zittis et al., 2016). Therefore, the negative impact of HWs is expected to increase in the future.

Agriculture in Chile is highly vulnerable to climate change especially in terms of extreme events and therefore increasing trends in the HW variables could diminish agricultural production (Marengo et al., 2014). The glaciers in the Andes of Chile seem to be shrinking and possibly losing mass (Pellicciotti et al., 2014). Increasing trends in the HW aspects could accelerate these processes and activate a set of negative effects. The scientific information on HWs occurring in Chile is quite limited. Few studies considering larger areas showed significant increasing trends in some HW indices for Chile (Donat et al., 2013; Skansi et al., 2013; Ceccherini et al., 2016).

The main aim of this study is to provide a multidimensional insight on changes recorded in HWs over the Chilean territory during the extended summer period (November–March) from 1961 to 2016 and briefly describe the climate regime of these events. No similar studies have been carried out in Chile until now.

2. Data and methods

2.1. Study area

The studied area is located in southwestern South America (17°30′S to 56°30′S latitude and 66°30′W to 75°30′W longitude) (Fig. 1). Its unique shape, geographical position and local morphology contribute to a wide variety of climate conditions (Valdés-Pineda et al., 2016). In Chile, the mean annual precipitation generally increases from North to South, while the mean annual temperature decreases in the same direction. Northern Chile (17°30′-30°00′S) is one of the driest areas on the planet (Schulz et al., 2012). The region situated between 17°30′S and 26°00′S latitude in the Atacama Desert is under hyperarid conditions with annual mean precipitation of < 1.7 mm (Barrett et al., 2016). Between 26°00′S and 31°00′S, the amount of precipitation increases and

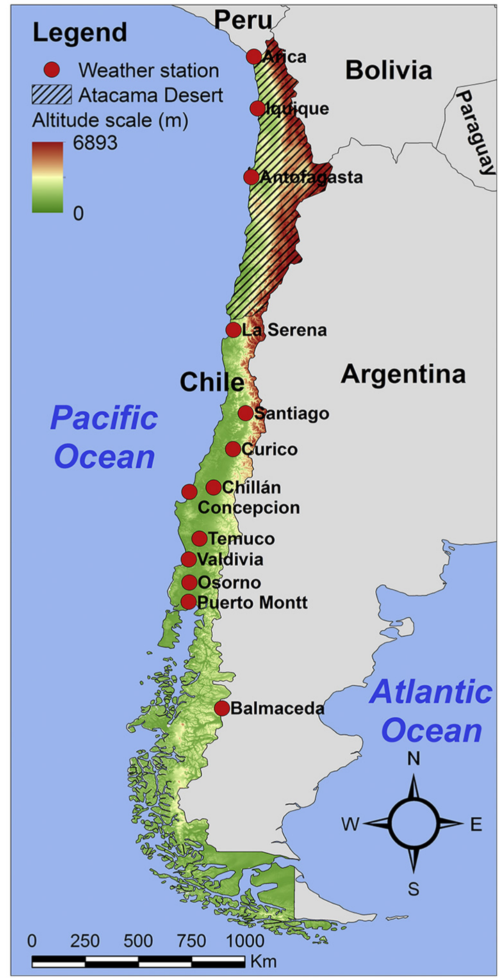

Fig. 1. Study area and locations of the weather stations.

Atacama slowly transits from hyperarid to semiarid climate conditions, due to more frequent winter cold frontal passages (Barrett et al., 2016). The dry conditions of the Atacama Desert result from the significant temperature inversion at the top of the marine boundary layer originated by an intense subsidence of dry air aloft in the domain of the quasi-permanent southeast Pacific anticyclone (SEPA), which drastically inhibits the development of convection and precipitation (Schulz et al., 2012). The relatively cold surface water associated with the Humboldt Current and the intense coastal upwelling forced by the southerly wind along the coast further contribute to the high stability of the atmosphere (Schulz et al., 2012). Finally, the barrier effect of the massive mountain range of the Andes prevents the advection of moist air from the Amazon basin, while the intensified subsidence in the troposphere associated with the sea-land contrast (Rutllant and Ulriksen, 1979; Rutllant et al., 1998, 2003) decisively contributes to the preservation of a hyper-arid environment in the close vicinity of the ocean (Schulz et al., 2012). The central regions of Chile (30°00′-38°00′S) where most of the population and economic activities are concentrated, benefit from semi-arid and Mediterranean climate, with annual precipitation ranging from 300 to 500 mm to up to 1500 mm in the south and at the foothills of the Andes (Bozkurt et al., 2017). At high altitudes in the Andes the mean annual precipitation can reach 3000 mm (Demaria et al., 2013). The central-southern regions of Chile (38°00′-56°30′S) are dominated by temperate humid-oceanic climate, while the south and extreme south areas record mainly cool oceanic and tundra climate.

Table 1
Geographical coordinates of the weather stations considered.

No	Station name[a]	Latitude	Longitude	Altitude (m)	TX missing data (%)	TN missing data (%)
1	Arica	−18°20′55″	−70°20′19″	58	0.1	0.2
2	Iquique	−20°32′07″	−70°11′53″	52	0.1	0.1
3	Antofagasta	−23°26′40″	−70°26′42″	135	0.1	0.2
4	La Serena	−29°54′59″	−71°12′58″	142	0.1	0.1
5	Santiago	−33°26′42″	−70°41′58″	520	0.1	0.1
6	Curico	−34°58′00″	−71°14′59″	228	0.2	0.1
7	Chillán	−36°34′58″	−72°02′54″	124	2.2	2.2
8	Concepcion	−36°46′22″	−73°03′47″	12	0.1	0.1
9	Temuco	−38°45′01″	−72°38′14″	114	2.6	2.6
10	Valdivia	−39°37′58″	−73°05′11″	19	2.2	3.3
11	Osorno	−40°36′41″	−73°03′38″	65	2.3	2.2
12	Puerto Montt	−41°25′20″	−73°05′38″	85	0.3	0.3
13	Balmaceda	−45°55′59″	−71°41′13″	520	0.2	0.5

[a] Weather stations are ordered from North to South.

Table 2
Heat wave indices (after Alexander and Herold, 2016).

Index	Description	Unit
TX_HWN TN_HWN EHF_HWN	The number of HWs (HWN) that occur in each extended summer according to each definition (TX, TN, and EHF)	Events
TX_HWF TN_HWF EHF_HWF	The number of days that are included in HW events (HWF) that occur in each extended summer according to each definition	Days
TX_HWD TN_HWD EHF_HWD	The duration of the longest HW (HWD) that occur in each extended summer according to each definition	Days
TX_HWM TN_HWM EHF_HWM	The mean magnitude of all HW (expressed as the mean value of all events) in each extended summer according to each definition	°C for HW magnitude based on TX and TN and °C^2 for that based on EHF
TX_HWA TN_HWA EHF_HWA	The peak daily value in the hottest HW in each extended summer according to each definition	°C for HW amplitude based on TX and TN and °C^2 for that based on EHF

2.2. Data

The HWs were identified based on daily TX and TN recorded at 13 weather stations in Chile over a 56-yr. period (1961–2016) (Fig. 1 and Table 1). Data sets were freely downloaded from the *Latin American Climate Assessment and Dataset* project database (non-blend data) (Martinez et al., 2012). Unfortunately for Chile, data were only available from 1961 to 2010. We also employed data for the uncovered remaining period (2011–2016), which was provided by the Dirección Meteorológica de Chile, so as to highlight the most recent signals of climate change and variability and provide the most updated results. Therefore, data sets are extensive and recent enough to detect and analyze trends and produce accountable results.

2.3. Methods

2.3.1. Data quality control

At a primary stage of data quality control (QC) some of the weather stations were eliminated because they did not meet the requirements of the World Meteorological Organization (WMO) of having < 5% missing data. Other two stations were excluded from the analysis due to their identical data sets. Finally, data from 13 weather stations were considered for further analysis. In Table 1, the percentage of missing data for each weather station is indicated.

Furthermore, data sets were also checked for quality with ClimPACT2 software (Alexander and Herold, 2016). Seven tests were performed on the data to ensure their reliability.

i. The potential outliers were identified by using an interquartile range (IQR) at monthly time-scale.
ii. The occurrence of four or more equal consecutive values in temperature data was tested.
iii. Values exceeding 50 °C were verified.
iv. The difference between two consecutive values, equal to or higher than 20 °C, were flagged.
v. The cases in which the TX was lower than the TN of the same day were considered for elimination.
vi. Also, the cases in which TX and TN were higher than 4 standard deviations away from their respective means were flagged.
vii. Rounding problems were also taken in consideration in the QC process. It was evaluated how often each of the ten possible values after the decimal point (0.0 to 0.9) appeared. If one or more values are more or less frequent than others, one might consider to discard the data set or use a statistical approach to restitute the data.

The QC techniques are described in detail in the user guide of ClimPACT2 software (Alexander and Herold, 2016) and in other recent studies (Croitoru et al., 2016; Piticar et al., 2017). After employing the QC tests on the data sets few erroneous data were found and therefore excluded.

2.3.2. HWs identification

In the present study, three definitions were employed to identify HWs. They are all recommended by the Expert Team on Sector-Specific Climate Indices (ET-SCI) of the WMO Commission for Climatology and Indices (CCl) in cooperation with experts in agricultural meteorology, water resources, hydrology, and health. These definitions were chosen due to their applicability to virtually all regions of the world, the quality of data required to calculate them, and the feasibility of their methodology (Perkins and Alexander, 2013). They can also be applied in a large range of sectors. The three HW definitions chosen for this study are described below:

1. the daytime TX exceeds the 90th percentile for at least three consecutive days;
2. the nighttime TN exceeds the 90th percentile for at least three consecutive days;
3. the Excess Heat Factor (EHF) is positive for at least three consecutive days.

The EHF as defined by Nairn and Fawcett (2013, 2015), WMO and WHO (2015), and Alexander and Herold (2016) is a new measure of HWs based on two excess heat sub-indices (EHIs) incorporating both TX and TN temperatures:

$$EHI_{sig.} = [(Tm_i + Tm_{i-1} + Tm_{i-2})/3] - Tm90_i \quad (1)$$

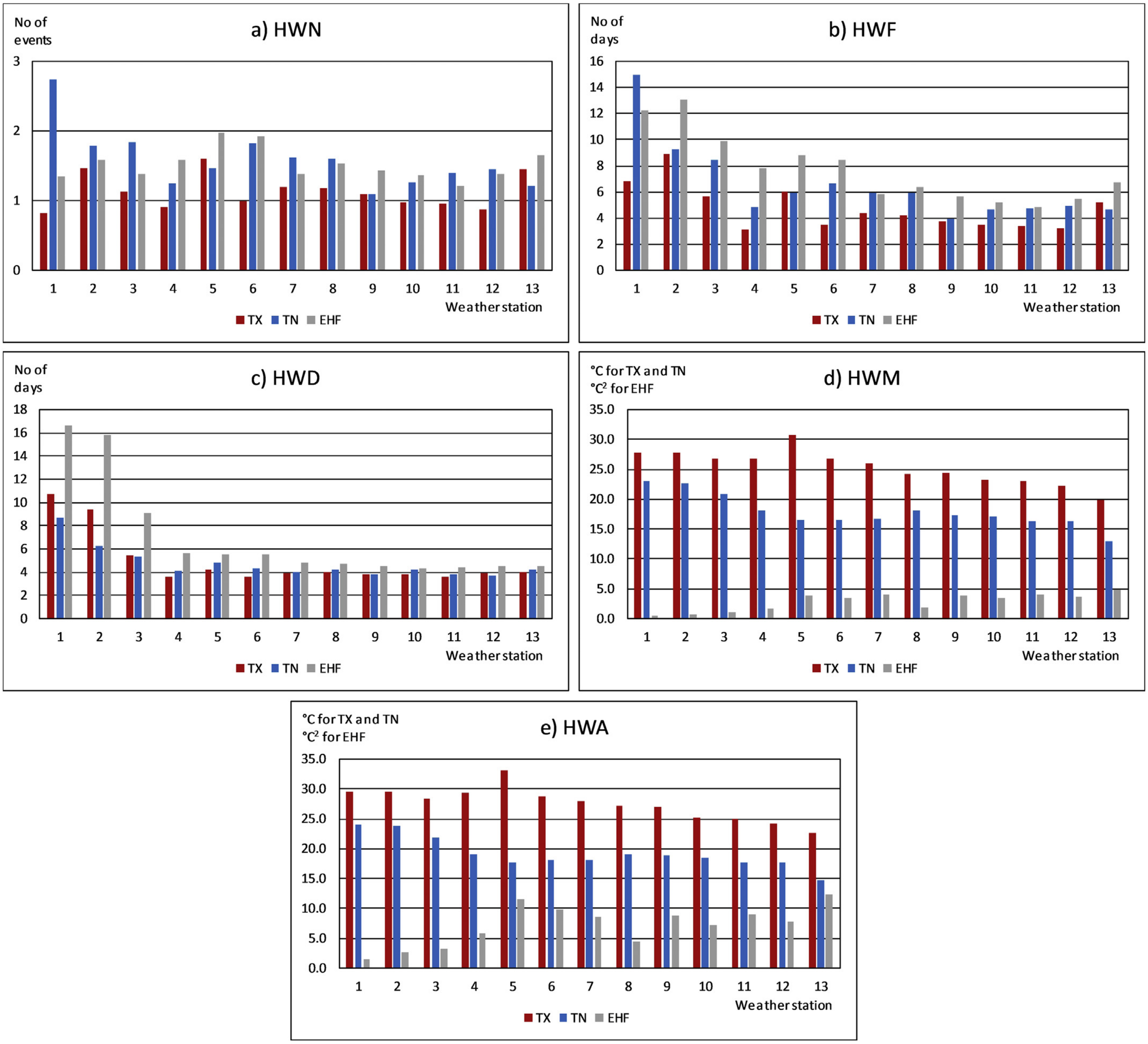

Fig. 2. Mean values of HW indices over the period 1961–2016 for the number of HWs in each extended summer (a), the number of days that are included in HW events (b), the maximum duration of the longest event (c), the mean value (magnitude) of all events (d), the peak daily value of the hottest event in the extended summer interval (e).

and,

$$EHI_{accl.} = [(Tm_i + Tm_{i-1} + Tm_{i-2})/3] - [(Tm_{i-3} + ... + Tm_{i-32})/30] \quad (2)$$

where $EHI_{sig.}$ describes the anomaly over a three-day period against the 90th percentile and $EHI_{accl.}$ is the anomaly of the same three-day period against the preceding 30 days. Tm is derived as Tm = (Tmax + Tmin)/2 and Tm_i is the average daily temperature for day *i*. The original definition uses the 95th percentile to calculate the $EHI_{sig.}$ (Nairn and Fawcett, 2013). However, in this study the 90th percentile was employed in order to be consistent with the intensity threshold considered by the other two HW definitions. Other studies also calculated the $EHI_{sig.}$ based on the 90th percentile for the same reason (Gross et al., 2017; Loughran et al., 2017).

While the $EHI_{sig.}$ sub-index refers to significant heat excess against long-term climatic conditions, the $EHI_{accl.}$ considers that people acclimatize to their local climate, with respect to air temperature within 30 days, and may not be prepared for a sudden warming above the temperature of the recent past (Nairn and Fawcett, 2015).

Eqs. (1) and (2) are then combined and the EHF is obtained:

$$EHF = \max[1, EHI_{accl.}] \times EHI_{sig.} \quad (3)$$

where positive values of EHF define heat wave conditions for day *i*. Therefore, these conditions (EHF > 0) must persist for at least three consecutive days for an HW to occur. Unlike Nairn and Fawcett (2013, 2015) who define HWs when EHF is positive, in this paper we extend this definition, following Perkins and Alexander (2013), so as to be able to analyze the aspects of HWs, namely intensity, duration, and frequency, and ensure that conditions persist long enough for the event to be considered an HW (Evans et al., 2017; Gross et al., 2017). For a positive EHF value to occur on day *i*, the average temperature over a three-day period (day *i*, day *i*-1, and day *i*-2) must be above the 90th percentile of long-term climate, which does not necessarily imply that

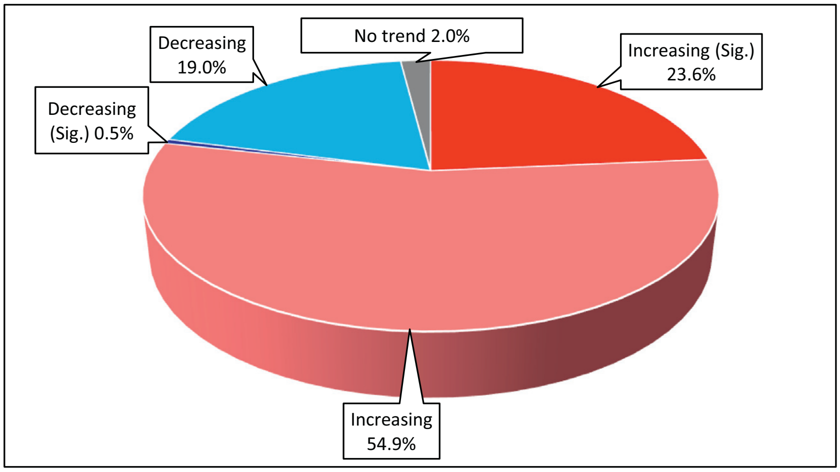

Fig. 3. Frequency of trend types in all HW indices from 1961 to 2016.

all days within the three-day period will be hot (> 90th percentile) (Perkins and Alexander, 2013; Gross et al., 2017). Thus, for a three-day HW to occur, day i, day $i + 1$ and day $i + 2$ must all have positive EHF values (Gross et al., 2017).

Whilst Perkins and Alexander (2013) have identified EHF as a useful measure for studying the impact of extreme heat events on human health and mortality, this does not preclude its usefulness to other sectors.

The percentile thresholds for all three definitions were calculated using the reference period of 1961–1990 and a 15-day window centered on each day of the calendar throughout the November–March interval.

Extending the threshold to at least three-day period for the identification of HWs was motivated by studies on human responses to the onset of extreme hot weather events according to which it takes three days or more of very hot weather for the mortality rate to rise significantly above its antecedent rate (Nairn and Fawcett, 2015). However, it is worth mentioning that a significant rise in human mortality can be expected from the very first day of HW conditions or even in the case of independently high temperature days, as indicated by Montero et al. (2012) in a study over Castile-La Mancha region (Spain) or by Guo et al. (2017) in a multi-country study.

In order to identify early and late HWs, we took into consideration the extended summer period of the year (November–March).

2.3.3. *HW aspects*

For each definition of HWs five aspects related to frequency, duration, and intensity were calculated and analyzed:

a. number of HWs (HWN) in each extended summer;
b. number of days included in HW events (HWF) in the extended summer period;
c. maximum duration (in days) of the longest event (HWD) in each extended summer;
d. magnitude of HWs (HWM) which is the mean value of all events in each extended summer (°C for the definitions based on TX/TN and °C^2 for the EHF);
e. amplitude of HWs, which represents the peak daily value of the hottest event in the extended summer interval (°C for the definitions based on TX/TN and °C^2 for the EHF).

Finally, some 15 indices of HWs were computed based on the five aspects of each definition (Table 2). All calculations were performed with the ClimPACT2 software (Alexander and Herold, 2016).

2.3.4. *Trend detection*

The Ordinary Least Square (OLS) method was used to detect the direction (upward or downward) and magnitude of the trend, whereas the statistical significance of change was computed based on Student's *t*-test. The slopes of the time series were calculated as change per decade. A trend was considered statistically significant at a 5% level ($p < .05$). These methods are largely used to assess changes in climate variables (Spinoni et al., 2015; Anandhi et al., 2016). Both methods are also included in the ClimPACT2 software (Alexander and Herold, 2016).

3. Results

3.1. *Climate regime of HWs*

The results of HW climatology over the study area are summarized in Fig. 2. With reference to all three definitions (Fig. 2a), the territory of Chile experiences on average between 0.8 and 2.7 events per extended summer. When TN was considered for HWs detection, the highest frequency was registered at Arica station (station 5) with > 2.5 events per extended summer. The highest frequency according to the EHF definition was recorded at Santiago and Curico stations (stations 5 and 6) (about 2 events per extended summer). We can note that HWs were on average more frequent in the area under study when they were identified based on TN and EHF than those identified based on TX. Only the HWs identified based on TN exhibited a more noticeable spatial pattern, decreasing from north to south. This pattern is more distinct in the case of HWF aspect revealing a decrease from northern to southern regions for all three HW definitions (Fig. 2b).

The HWs with the longest durations (HWD) in each extended summer generally have similar values for all three definitions employed and for most of the weather stations (Fig. 2c). The longest events in each extended summer had a value of 4 days on average in central and southern regions. Only three stations (stations 1–3) located in the Atacama Desert indicated higher values especially for HWD measured by EHF definition (up to > 16 days per extended summer). Also, HWD values for EHF definition are the highest at all weather stations when compared to the definitions based on TX and TN.

The average magnitude of all HWs recorded in the extended summer period (HWM) mainly decreased from north to south when it was calculated by TX and TN and increased when it was identified by EHF definition (Fig. 2d). In the case of EHF, the opposite pattern of HWM may be explained by the dependency of this index to other aspects such as HWN, HWF and HWD. Thus, the number of HWs and their duration can induce a different behavior in the spatial distribution of EHF_HWM.

The HWA aspect measuring the daily peak value of the hottest HW in the period of November–March had similar spatial distribution when compared to that of HWM for all three definitions. The highest values of

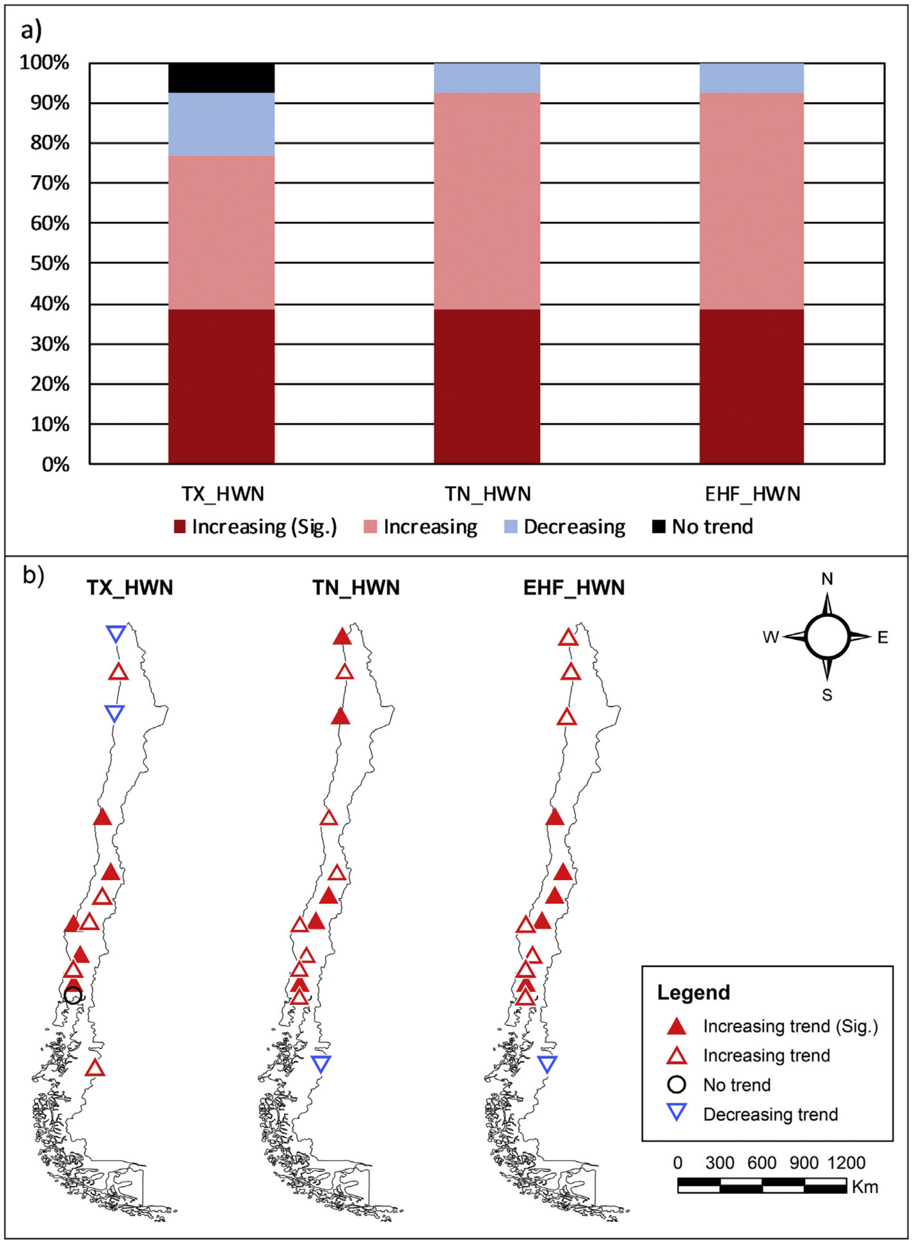

Fig. 4. Frequency (a) and spatial distribution (b) of trends in HWN indices from 1961 to 2016.

HWM and HWA aspects calculated using TX were recorded at Santiago weather station (station 5) indicating that the most intense daytime events occurred in the most populated area of Chile.

On the whole, the results suggest that the Atacama Desert along with Santiago metropolitan area are the most extreme regions of Chile in terms of HW aspects. The urban heat island of Santiago, which can reach an intensity of 5 °C in summer, and the city location in an inland closed basin surrounded by the Coastal and Andes mountains can be at least partly responsible for the results shown at this weather station (Peña, 2008; Sarricolea and Martín-Vide, 2014). Moreover, the maritime influence of the Pacific weakens inland could also substantially alter the results obtained at Santiago weather station (station 5) (Burger et al., 2018).

3.2. Changes in HW indices

Changes in HWs in Chile are first presented as a whole and then in sub-sections related to each aspect, describing their characteristics: HWN, HWF, HWD, HWM and HWA.

In order to investigate the changes in HWs, three definitions and five aspects for each definition were used. Thus, a total of 15 indices resulted creating a comprehensive image on the changes occurred in these events. For each index the direction of trends (upward or downward), their statistical significance ($p < .05$), magnitude (slope) and spatial distribution were analyzed. Results indicated an important increase in HW indices in Chile (Fig. 3). Thus, the frequency of trend types analysis of all HW indices time series showed an increasing trend of 79%. Out of all time series, about 24% increased statistically significant. Decreasing trends were found in 20% of time series, whilst statistically significant downward trends were < 1% frequent. Stationary trends were detected in only 2% of the series.

3.2.1. Heat wave number (HWN)

The results of changes in HWN are given in Figs. 4a, b and Table 3. The analysis of HWN data revealed that almost all of the time series had an upward trend (77% for TX, and 92% for TN and EHF). Out of all

Table 3
Slopes[a] of HWs indices over the period 1961–2016.

HW index	Arica	Iquique	Antofagasta	La Serena	Santiago	Curico	Chillán	Concepcion	Temuco	Valdivia	Osorno	Puerto Montt	Balmaceda
TX_HWN	−0.11	0.01	−0.18	**0.20**[b]	**0.30**	0.11	0.12	**0.25**	**0.27**	0.14	**0.17**	0.00	0.11
TN_HWN	**1.15**	0.43	**0.49**	0.24	0.18	**0.45**	**0.30**	0.22	0.05	0.09	**0.31**	0.10	−0.01
EHF_HWN	0.25	0.31	0.16	**0.35**	**0.48**	**0.47**	**0.30**	0.23	0.16	0.14	**0.23**	0.02	−0.04
TX_HWF	−0.30	0.38	−0.39	0.67	**1.38**	**0.55**	0.57	**1.12**	**0.83**	0.49	0.47	0.11	0.41
TN_HWF	**6.32**	2.68	2.46	0.90	0.86	**1.82**	**1.25**	0.79	0.24	0.34	**1.16**	0.39	0.00
EHF_HWF	2.21	2.64	1.39	1.52	**2.55**	**2.11**	**1.15**	0.80	0.56	0.48	**0.90**	0.15	−0.23
TX_HWD	1.08	0.73	0.15	0.05	**0.40**	0.19	**0.19**	**0.41**	−0.04	0.00	−0.08	0.17	0.14
TN_HWD	0.86	0.49	0.63	0.02	0.20	**0.38**	0.09	0.06	0.10	0.01	0.18	0.02	0.06
EHF_HWD	0.39	0.33	0.55	0.07	**0.69**	0.10	−0.12	−0.06	0.05	−0.16	−0.02	0.08	−0.08
TX_HWM	0.16	**0.56**	0.21	0.03	0.00	**0.40**	0.27	0.08	0.39	0.08	−0.16	0.14	0.12
TN_HWM	−0.08	0.01	0.02	−0.07	−0.05	0.10	0.03	0.02	−0.08	−0.02	**−0.19**	−0.11	−0.02
EHF_HWM	0.02	0.01	−0.02	−0.03	0.14	**0.61**	**0.69**	0.07	−0.01	−0.05	0.23	0.16	0.20
TX_HWA	0.02	**0.89**	0.30	**0.59**	**0.41**	**0.54**	**0.52**	0.38	**0.89**	0.21	−0.22	0.36	0.50
TN_HWA	−0.03	−0.01	0.03	−0.08	−0.01	**0.42**	0.25	0.08	0.01	0.02	−0.12	−0.10	−0.15
EHF_HWA	0.12	0.31	−0.18	0.04	**1.81**	**1.77**	**1.33**	0.38	0.78	−0.09	0.35	0.10	−0.50

[a] The slopes are calculated as change per decade.
[b] Bold indicates significance at 0.05 level.

increasing trends, about 39% were found to be statistically significant for all HW definitions employed (Fig. 4a). Only a few stations located in the northern (in the case of TX_HWN) and southern regions (in the case of TN_HWN and EHF_HWN) had a decreasing trend but they were statistically insignificant (Fig. 4b). In the case of HWN identified based on TX and EHF definitions, significant increasing trends had similar spatial patterns and were recorded only in the central areas of Chile. When analyzing HWN based on TN it can be noted that significant increasing trends are concentrated in northern and central regions.

Regarding trend magnitude, the highest values were recorded for TN_HWN index, while the HWN identified based on TX had the lowest values indicating that the occurrence of nighttime events is increasing faster than daytime HWs (Table 3). Over the 1961–2016 time span, the significant increasing trends had a magnitude of 0.17–0.30 events/decade for TX_HWN, while for the other two indices related to HWN they recorded between 0.30 and 1.15 events/decade for TN and between 0.23 and 0.48 events/decade for EHF. The fact that most slopes are positive for all three definitions indicates that the increasing trend in HWN is predominant in Chile.

Since most of the Chilean population and activities are concentrated in the central areas, the significant increase in HWN in this region may cause adverse effects on various components such as human health, infrastructure and agricultural activities.

3.2.2. Heat wave days frequency (HWF)

Results of changes in the frequency of days that contribute to all HWs in the extended summer period are presented in Figs. 5a, b and Table 3. Increasing trends were observed in > 80% of time series for the HWs identified by TX and in > 90% for those calculated by TN and EHF. Statistically significant increasing trends in HWF were detected in 31% of the stations for all three HW definitions. Decreasing and stationary trends were recorded only in a few locations but they were statistically insignificant.

The magnitude of significant increasing trends ranged between 0.83 and 1.38 days/decade for TX_HWF, between 0.9 and 2.55 days/decade for EHF_HWF, whereas for the TN_HWF it ranged from 1.16 to 6.32 days/decade during the 1961–2016 period. As in the case of HWN, the magnitude of significant increasing trends was the highest for HWs measured by TN when compared to those computed based on TX and EHF.

The spatial pattern of HWF trends is very similar to HWN for all definitions employed: generalized increasing trends across all regions, significant increasing trends concentrated mostly in the central areas for all three definitions, and a few isolated stationary and decreasing trends in the northern and southern regions. A similar pattern of changes between HWF and HWN was expected since a change in the HWF is directly causing a change in HWN and vice versa (Perkins and Alexander, 2013; Piticar et al., 2017).

3.2.3. Heat wave duration (HWD)

Figs. 6a, b and Table 3 show the frequency of each trend type of the longest yearly event, their spatial distribution and decadal rates of change. About 77% of the weather stations recorded an upward trend in TX_HWD index statistically significant in 23% of cases, suggesting that the maximum duration of prolonged daytime extremely high temperature has increased (Fig. 6a). Significant increasing trends have raised from 0.19 to 0.41 days/decade (Table 3). Decreasing trends were only found in two weather stations located in the central-southern areas. The longest periods of high temperature at nighttime (TN_HWD) increased in their duration in all stations across Chile. However, only the Curico station (station 6), located in the central area, recorded a significant trend. In the case of EHF_HWD index, upward trends were found in 62% of the weather stations. The increase was significant in only one location (Santiago).

The spatial distribution analysis showed that increasing trends of EHF_HWD are concentrated mainly in the northern half of the country, while decreasing trends were found in central and southern regions. The significant increasing trends follow a similar spatial pattern for all three definitions concentrating in the central region of Chile suggesting that this area seems to be the most exposed to significant changes in the HWD aspect.

3.2.4. Heat wave magnitude (HWM)

HWM is the average daily magnitude across all heat wave events in the extended summer period within a year. It is worth mentioning that, unlike other aspects analyzed in this paper, HWM is strongly related to the number of HWs and their duration, and implicitly to HWF. Thus, a longer or shorter HW and a higher or lower frequency of HWs can influence HWM and induce different trends than expected. The magnitude of HWs over the period November–March increased in the case of 85% of the weather stations when it was calculated based on TX, thus indicating that HWs became hotter (Figs. 7a, b). The increase was statistically significant in 15% of the stations. In the case of TN_HWM index, the magnitude of trends decreased in the central-southern regions of Chile during the extended summer period. Few isolated decreasing trends were also observed in the central and northern areas of the country. Increasing trends of TN_HWM were present in the northern and central areas (39%). None of the upward trends were statistically significant. When the magnitude of HWs was calculated based on EHF, results indicated an overall increasing trend in all areas. However, only few statistically significant increasing trends were found and they were concentrated in the central regions of the country. Downward trends

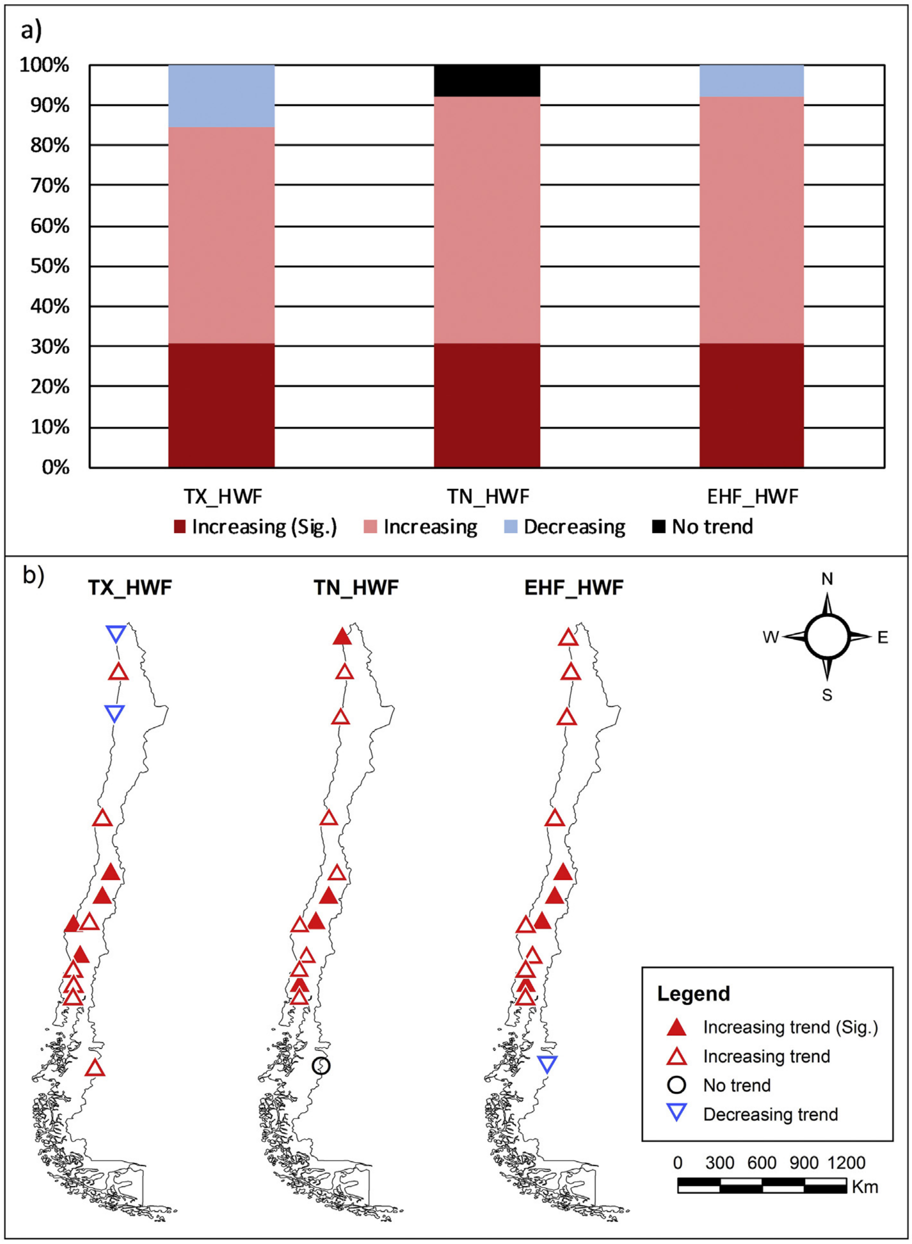

Fig. 5. Frequency (a) and spatial distribution (b) of trends in HWF indices from 1961 to 2016.

were observed in 31% of the stations.

The slopes of trends are presented in Table 3. Positive slopes ranged between 0.03 and 0.56 °C/decade for TX_HWM. In the case of TN_HWM the positive rates of change were between 0.01 and 0.10 °C/decade. The analysis of EHF_HWM index indicated that positive slopes varied from 0.01 °C2/decade to 0.69 °C2/decade. Because of the dependency of HWM to HWN, which is used as the denominator for its calculation, along with a less consistent variability among TX_HWN, TN_HWN, and EHF_HWN (Supplementary material no. 1) comparisons between the rates of changes for different definitions should be avoided.

3.2.5. *Heat wave amplitude (HWA)*

HWA represents the value of the hottest day during the hottest event recorded in an extended summer period. Changes in HWA are higher in terms of frequency of statistical significance and magnitude of slopes when compared to HWM (Fig. 8a and Table 3). These findings concur with the results of other studies (Perkins and Alexander, 2013; Croitoru et al., 2016; Piticar et al., 2017).

The rate of increase in TX_HWA over Chile ranged between 0.02 and 0.89 °C/decade (Table 3). Statistically significant increasing trends were recorded in 46% of the considered stations (Fig. 8a). Only one station located in the southern region of Chile had a decreasing trend (Fig. 8b). The spatial distribution of trends revealed that statistically significant increasing trends are mainly concentrated in the central regions of Chile.

When analyzing the HWA aspect based on TN, results showed that the central region is dominated by upward trends, while the northern and southern areas presented downward trends (Fig. 8b). Decreasing trends had a slightly higher frequency than the increasing ones. The results of the TN_HWA index suggest that the highest nighttime temperature during the hottest HWs did not significantly increase in the studied area.

The EHF_HWA has increased in almost 80% of the stations as shown in Fig. 8a. Significant increase has been recorded in 23% of the stations. The spatial distribution analysis indicated that the statistical significant increasing trends are concentrated in the central region of Chile

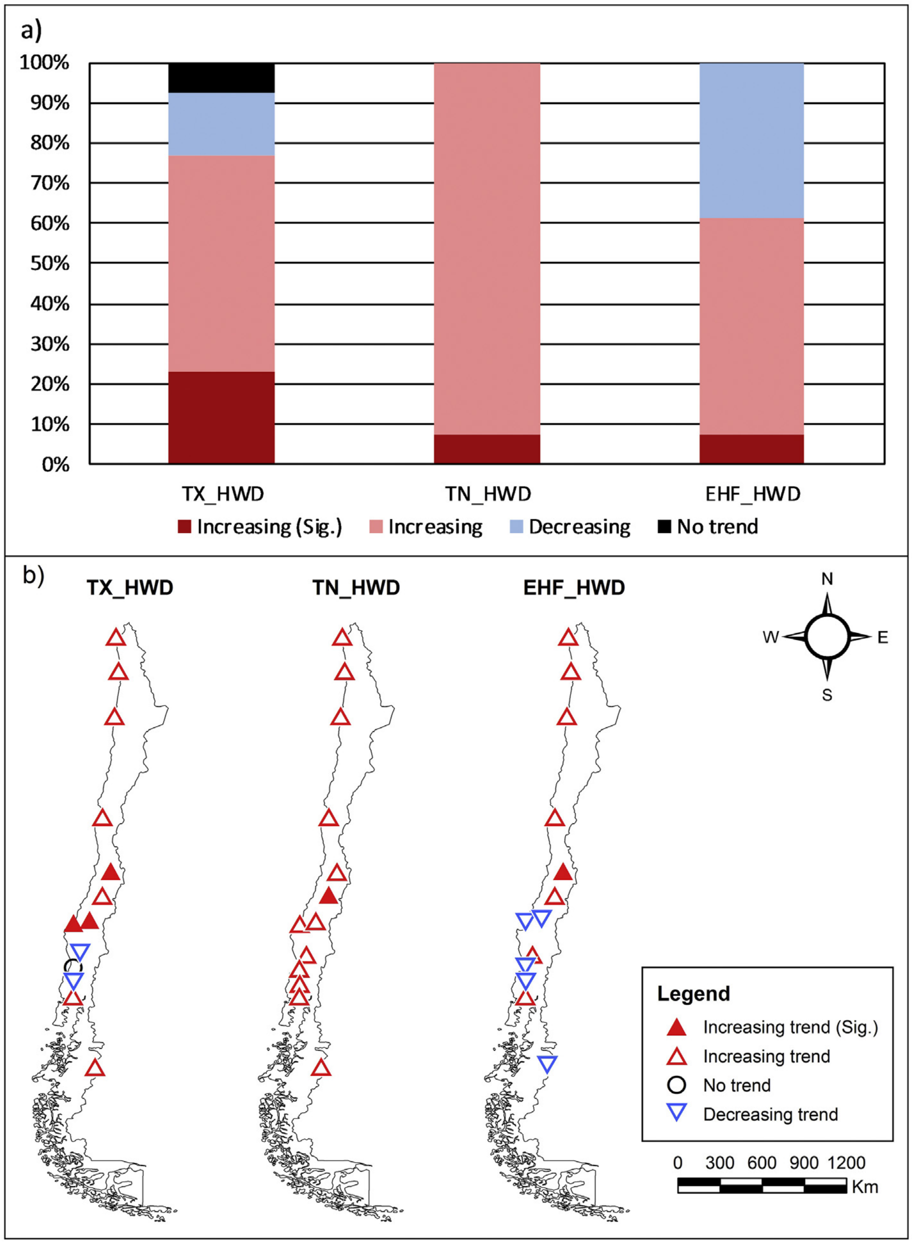

Fig. 6. Frequency (a) and spatial distribution (b) of trends in HWD indices from 1961 to 2016.

(Fig. 8b). Overall, the results of HWA based on all three definitions suggest that central areas experienced the most important change since most of the significant increasing trends are concentrated in these regions, and the magnitude of change is the highest. Moreover, even a small increase in the HWA aspect, when the atmospheric humidity is high, could exacerbate stress levels in the human body and other organisms (Fischer and Schär, 2010).

4. Discussions and conclusions

In this study, the HW climate regime and changes were analyzed based on three definitions in the period of 1961–2016 using data from 13 weather stations in Chile. Five aspects of HWs were employed and investigated for each definition resulting in a total number of 15 HW indices.

The HW indices showed a majority of increasing trends over the studied area. According to all three definitions employed, the increase was significant in almost 40% of the analyzed time series in the case of HWN, 30% in the HW days frequency, between 7.7% and 23.1% in the lengthiest events, between 0% and 15.4% in the magnitude of HWs, and between 7.7% and 46.2% for their amplitude. The highest frequency of statistically significant upward trends was found in the number of events and their amplitude (but only according to TX definition). With reference to their definition, the highest frequency of significant increasing trends was found in the HWs identified based on TX, followed by those computed based on EHF.

Overall, we found the largest trend magnitude in the case of HWN and HWF aspects when TN-HWs definition was employed, while in the case of HWD and HWM the highest values of trend magnitude were recorded for the TX-HWs definition. In other words, daytime events frequency increased the fastest when compared to the other two definitions, while the nighttime ones recorded the most accelerated increase in HWD and HWM. The HWA aspect increased the fastest according to the EHF definition.

An important conclusion to be drawn is that, regionally, the central area of Chile is the most affected by significant changes in HWs indices.

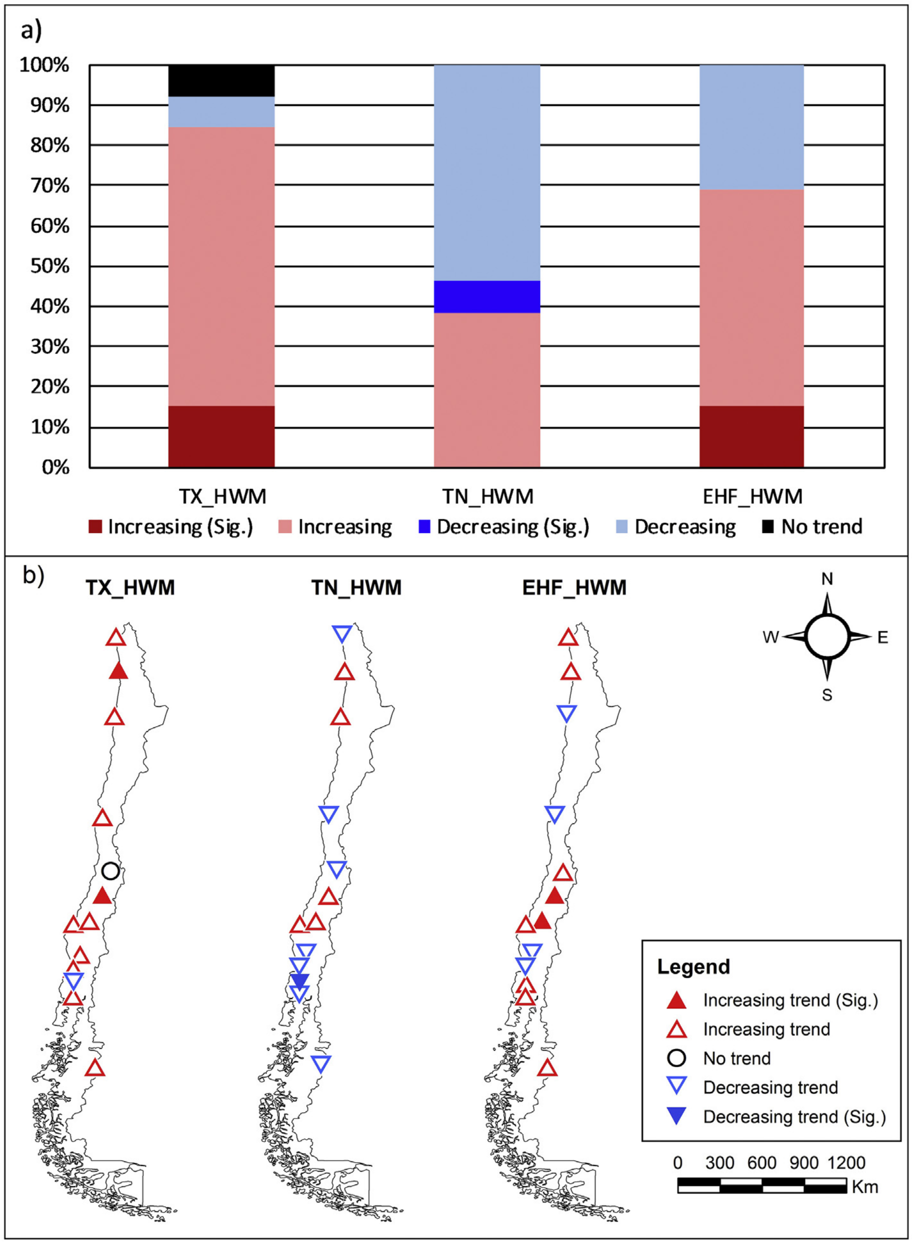

Fig. 7. Frequency (a) and spatial distribution (b) of trends in HWM indices from 1961 to 2016.

Vicuña et al. (2011) also showed important projections of climate change in terms of temperature (increase) and precipitation (decrease) in this region. All these changes will undoubtedly have severe consequences on water availability, biologic productivity, and already precarious ecosystems (Vicuña et al., 2011). Thus, central Chile is expected to become highly vulnerable to climate change and implicitly to changes in HWs, if rigorous adaptation strategies are not considered.

Regarding climate change and HW changes detection, a more prominent signal manifested in HWN, HWF, and HWA aspects. Essentially, we found that changes in the aspects of HWN, followed by HWF, generated the most robust pattern according to all HW definitions employed. Even though it is difficult to determine whether the cumulative change reflected in HWF is related to HWN and/or HWD, for the studied region, this change can be rather a reflection of changes occurred in HWN than one in HWD.

Given the fact that HW definitions employed in this study exhibited a few different results concerning their aspects and spatial distribution it is important to consider multiple definitions in order to understand their full behavior in every region of interest. Also, by investigating HWs using different characteristics (multiple definitions and aspects), we can better understand the intensity of changes, and provide the most appropriate information to those that need it the most (e.g. health researchers, ecologists, engineers, farmers).

In general, these results are highly consistent with results reported in many other regions of the world in which, despite the large variety of methodological approaches, increasing trends in HWs frequency, duration and intensity were found (Coumou and Rahmstorf, 2012; Perkins et al., 2012; Perkins and Alexander, 2013; Rusticucci et al., 2016; Ceccherini et al., 2016; Croitoru et al., 2016; Rohini et al., 2016; Panda et al., 2017; Piticar et al., 2017; Zhang et al., 2017).

We believe our work significantly contributes to the analysis of this topic in this part of the world especially considering that some authors stated that there is a lack of research on changes in HWs in South America (Hartmann et al., 2013; Rusticucci et al., 2016). Perkins et al. (2012) analyzed the same three HWs definitions based on HadGHNCD dataset at the global spatial scale and emphasized on the importance of

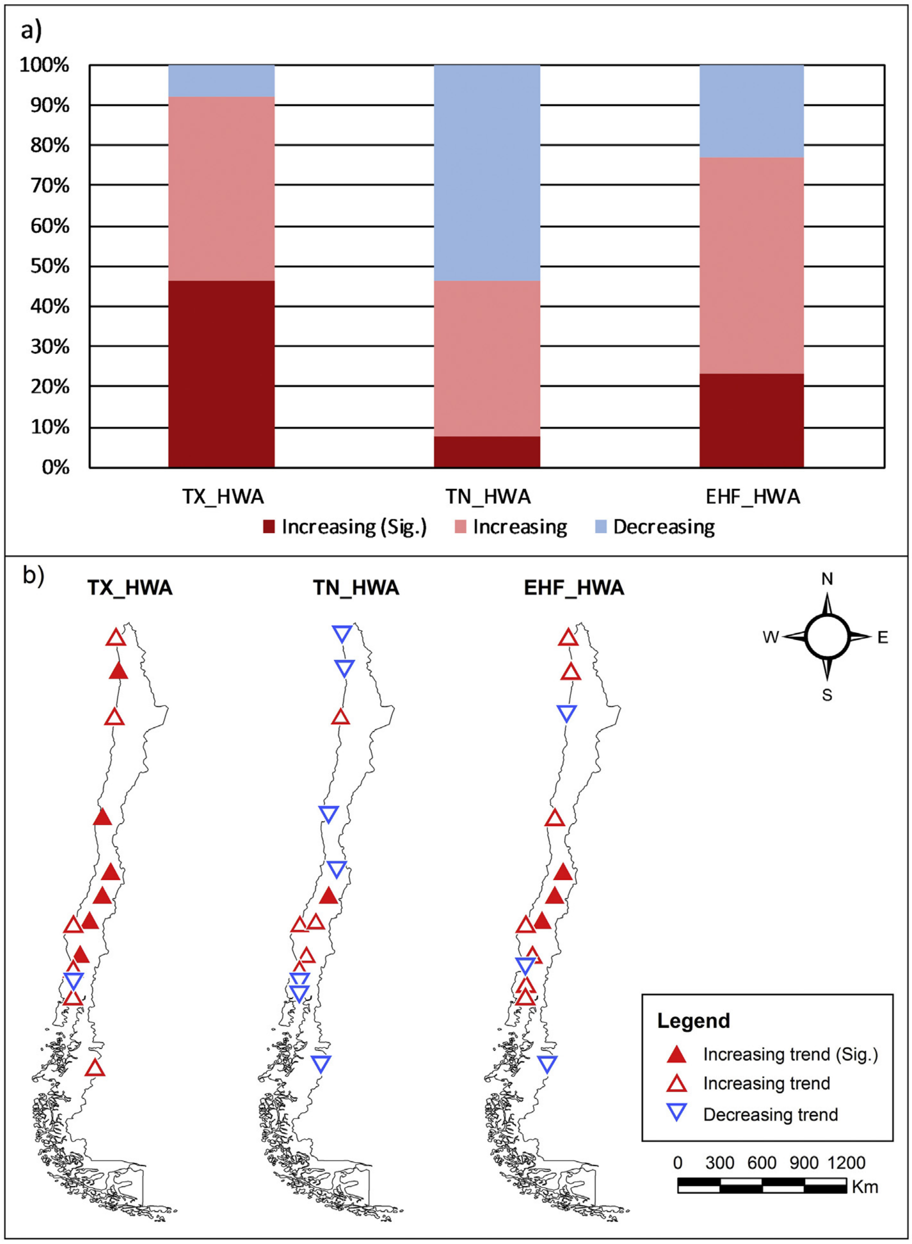

Fig. 8. Frequency (a) and spatial distribution (b) of trends in HWA indices from 1961 to 2016.

undertaking studies in regions with data sparse coverage and recommended using different observational datasets.

This study can only draw the potential impact of changes in HWs based on studies that were carried out in other parts of the world with different geographical characteristics, or considering different factors such as: population pyramid, adaptation or socioeconomic status. For instance, although the HW aspects substantially increased in most parts of the United States (Allen and Sheridan, 2016) and United Kingdom (Sanderson et al., 2017), heat-related mortality has been observed to decrease in these regions (Montero et al., 2012). On the contrary, heat-related mortality has increased in Castile-La Mancha (Spain) (Montero et al., 2012). Thus, further studies should investigate the effect of extreme temperatures in the form of HWs in different environmental and socioeconomic components in the studied area. Therefore, this study can be the foundation for future studies of the HW impact and can contribute to the development of adaptation plans in Chile. It can also broaden the knowledge and understanding of spatial-temporal distribution of HW indices across Chile.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2018.08.007.

Conflicts of interest

The author declares no conflict of interest.

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